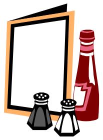
Electron Cooling

Sergei Nagaitsev
FNAL - AD
April 28, 2005

Accelerator Physics

- Particle motion in accelerator is governed primarily by classical physics laws:
  - Conservation of energy and momentum
  - Ampère's law: $d\mathbf{F}=I\,d\mathbf{l}\times\mathbf{B}$
  - Maxwell's equations
  - Coulomb's law for two point charges
  - Ohm's law or similar law relating voltage and current
- Liouville's theorem
  - J. Liouville, J. de Math. 3 (1838) 349.
  - In a conservative Hamiltonian system (such as a single particle in external magnetic and electric fields) the phase-space density is conserved.
  - Beam cooling methods must "get around the theorem" e.g. by pushing phase-space around.

Today's Menu



- What is cooling? Types of beam cooling
- Electron cooling
- Conclusions

Why cool?

- Particle accelerators, by imparting high energies to charged particles, create a beam in a state with a virtually limitless reservoir of energy in one (longitudinal) degree of freedom. This energy can couple (randomly and coherently) to other degrees of freedom by various processes, such as:
  - scattering;
  - improper bending and focusing;
  - interaction with environment (e.g. vacuum chamber)
  - radiation;
- Normally, it is necessary to keep energy spreads in the transverse degrees of freedom at 10^{-4} of the average longitudinal energy.

What is cooling?

- Cooling is a reduction in the phase space occupied by the beam.
- Equivalently, cooling is a reduction in the random motion of the beam.
- Since the random motion can be described as a temperature, beam cooling can be described as a reduction of the beam temperature.

Need for cooling

- Injection help: stacking, accumulation, phase-space manipulation etc.
- Rare isotope and antiparticle production: accumulation of many pulses of antiparticles
- Internal fixed target: emittance growth from target scattering
- Colliding beams: beam-beam effects, residual gas scattering, intra-beam scattering, rf noise
- Precise Energy Resolution: narrow states, threshold production

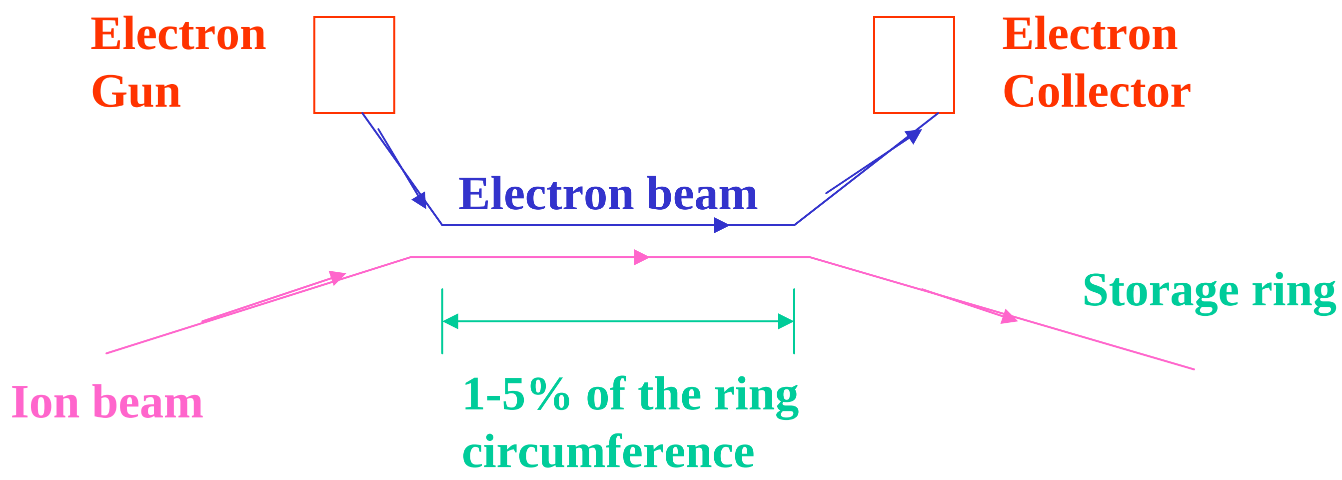
Types of cooling

- Longitudinal cooling due to acceleration
- Stochastic cooling
- Synchrotron radiation
- Electron cooling
- Laser cooling (of certain ion beams)
- Ionization cooling (not yet tested)
- Technique for rapid transverse cooling in a straight transport line has yet to be found.

How does electron cooling work?

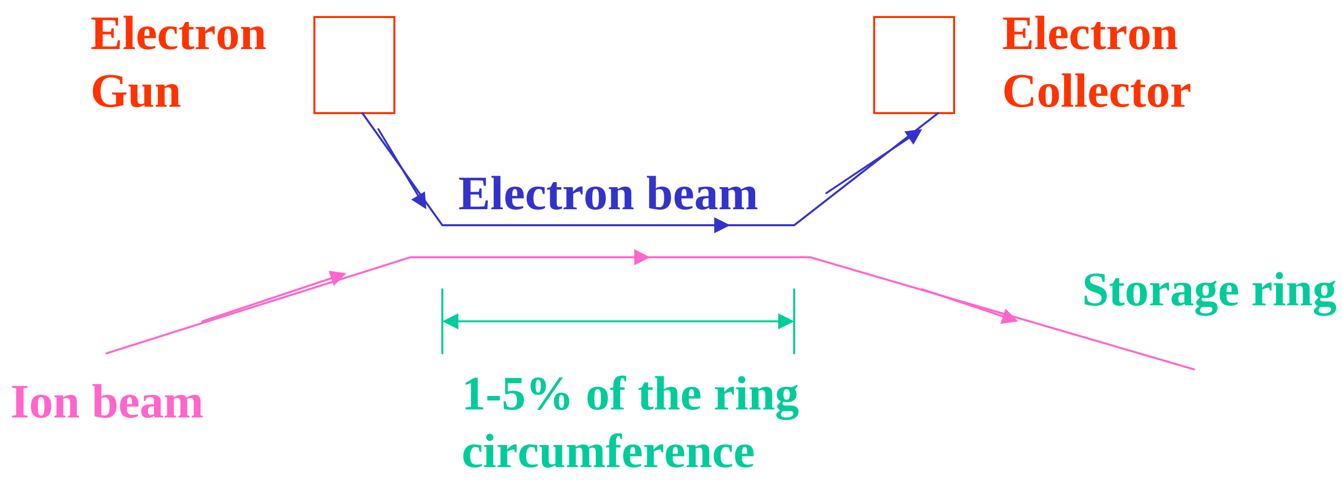
The velocity of the electrons is made equal to the average velocity of the ions.

The ions undergo Coulomb scattering in the electron "gas" and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



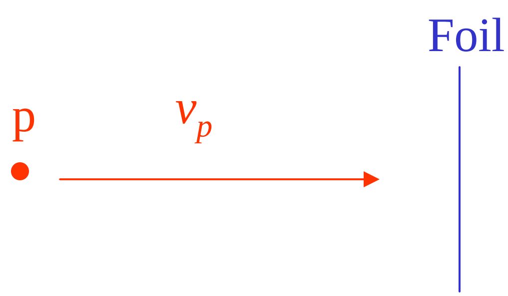
How does electron cooling work?

- Typical parameters of all existing low-energy electron coolers:
  - electron kinetic energy: 2-300 keV
  - ion kinetic energy: 4-600 MeV/nucleon
  - electron beam current: up to 5 A



Moving foil analogy

- Consider electrons as being represented by a foil moving with the average velocity of the ion beam.
- Ions moving faster (slower) than the foil (electrons) will penetrate it and will lose energy along the direction of their momentum (dE/dx losses) during each passage until all the momentum components in the moving frame are diminished.



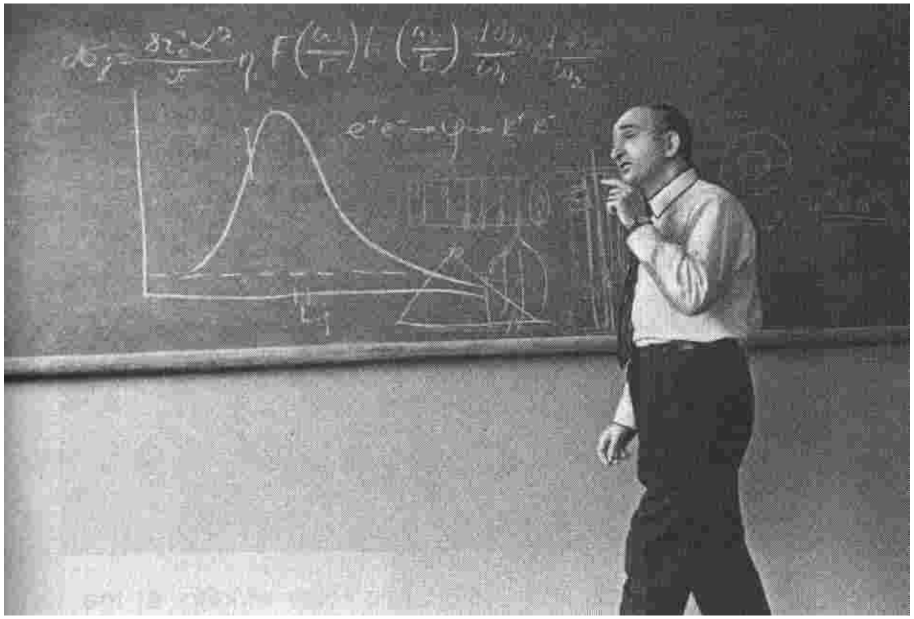
$$\vec{F}^* = -\nabla^* E^* = -\frac{4\pi n^* (r_e m c^2)^2 \Lambda}{m v_p^{*2}} \cdot \frac{\vec{v}_p^*}{v_p^*}$$

* represents rest frame

Electron cooling

- Was invented by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.

- First publication at Symp. Intern. sur les anneaux de collisions á electrons et positrons, Saclay, 1966: "Status report of works on storage rings at Novosibirsk"



Laboratoire de
l'Accélérateur Linéaire
ORSAY

Institut National des
Sciences et Techniques Nucléaires
SACLAY

SYMPOSIUM INTERNATIONAL
SUR LES ANNEAUX DE COLLISIONS
A ELECTRONS ET POSITRONS

Sous la présidence de

Monsieur Alain Peyrefitte

Ministre délégué chargé de la recherche scientifique
et des questions atomiques et spatiales

tenu à

l'Institut National des Sciences et Techniques Nucléaires, Saclay
26-30 Septembre 1966

Edité par

H. ZYNGIER
ORSAY

E. CREMIEU-ALCAN
SACLAY

STATUS REPORT OF WORKS ON STORAGE RINGS AT NOVOSIBIRSK

SHORT SUMMARY OF THE TALK GIVEN BY :

G.I. BUDKER

During the year elapsed since our last meeting in Frascati, the work in our Institute on colliding beams has been developed in three directions.

On electron-electron storage ring VEP-1 were performed high energy physics experiments : electron-electron elastic scattering [1] and double bremsstrahlung production for energies up to 2 x 160 MeV [2].

On electron-positron ring VEPP-2, we investigated the storing of electrons and positrons. After a first stage devoted to the understanding of numerous beam instabilities [3-7], experiments on electron-positron interaction at 2 x 380 MeV were undertaken [8]. Currents as high as 2 A of electrons and 20 mA of positrons were obtained with single beams, and 70 mA of electrons and 10 mA of positrons with interacting beams. At present time we already have detected some elastic scattering events at large angle and creations of π-meson pairs.

We have started working on the construction of our third set-up designed for proton-antiproton colliding beam experiments at energies up to 2 x 25 GeV. We are looking into the possibility of using this set-up also for electron-positron colliding beam experiments up to 2 x 6 GeV. It was decided that a second ring allowing proton-proton collisions will not be built since CERN undertook the construction of such a machine at a similar energy. The main tunnel for the machine is under completion. We are now experimenting different components of the system.

Fig. 1 shows the general lay-out of the set-up, with the accelerator-injector, the small and the big storage rings. The injector is an ironless proton synchrotron accelerating protons up to 500 MeV. Experiments on charge exchange injection into such a synchrotron have shown the possibility of obtaining currents near the space-charge limit [9].

Lack of radiation damping for heavy particles somewhat complicates their accumulation. We are working out in our Institute a method of artificial damping through interaction between the proton beam and an electron beam. In discussions with prof. O'Neill, I found out that they also contemplated such a method several years ago, and named it "electron cooling".

The stacking process in the proton-antiproton machine can be divided into several stages. The first one is the stacking of protons in the big storage ring. The length of the proton bunch in the synchrotron injector allows its capture in the large ring without loss of particles in one bucket of the 300th harmonic of the revolution frequency. After filling of the 300 buckets, the RF frequency is switched to the first harmonic. The particles are then accelerated to the maximum energy, and this reduces the bunch length approximately to the length of the small ring. Then the protons are ejected towards a special target to create antiprotons which are injected into the small ring.

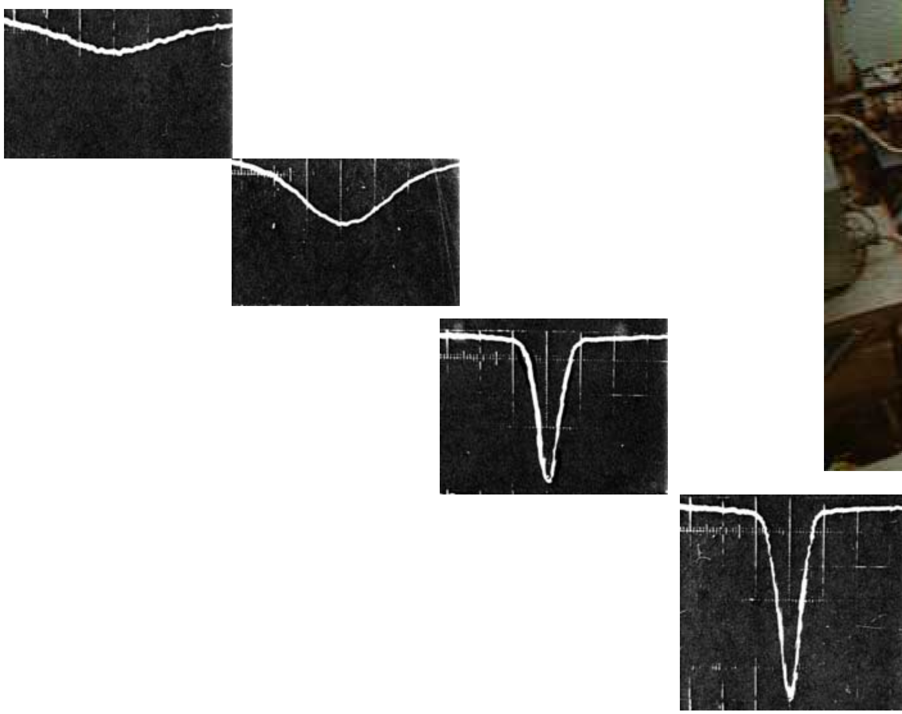
According to our estimations, electron cooling will take about 100 seconds. Then, for the lifetime of one day, we can have about 1000 cycles of antiproton injection. After that, antiprotons will be reinjected into the big ring where colliding beam experiments will be performed.

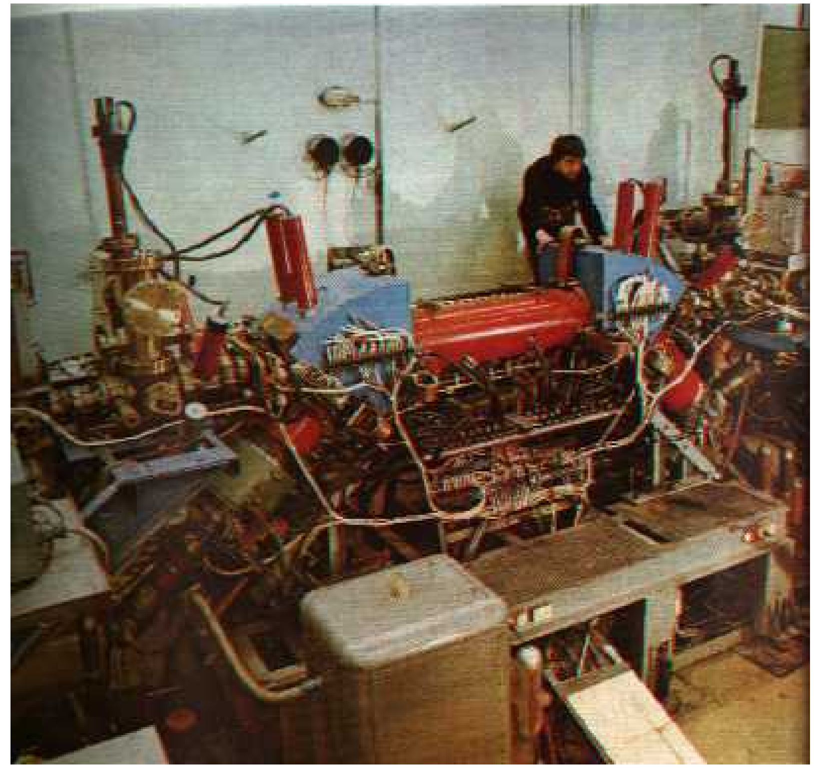
Gerard K. O'Neill (1927-1992)

- Was a professor of physics at Princeton University (1965-1985). He invented and developed the technology of storage rings for the first colliding-beam experiment at Stanford. He served as an adviser to NASA. He also founded the Space Studies Institute.

First Cooling Demonstration

- Electron cooling was first tested in 1974 with 68 MeV protons at NAP-M storage ring at INP(Novosibirsk).





IEEE Transactions on Nuclear Science, Vol.NS-22, No.5, October 1975

EXPERIMENTS ON ELECTRON COOLING

G. I. Budker, Ya. S. Derbenev, N. S. Dikansky, V. I. Kudelainen
I. N. Meshkov, V. V. Parkhomchuk, D. V. Pestrikov, B. N. Sukhina
A. N. Skrinsky

Institute of Nuclear Physics
Siberian Division

1974 - First experimental success and first report on electron cooling of protons in NAP-M :

E_p 50 MeV Ip 50 μA

E_e 27 keV Ie 0.1 A

$\phi_{p\_equilibrium}$ 1 mm

τ_{cool} 3 sec - in full agreement with Budker's theory (classical plasma formulae).

system, e and e_p are the electron and proton charges respectively, η is the ratio between the length of the orbit section occupied by the electron beam and its circumference, L≃20 is the Coulomb logarithm, c is the velocity of light.

Naturally, the cooling process kinetics is more complex. One should take into account the peculiarity of the proton beam motion in a storage ring as well as

Main Results

p	50 MeV;	50 μ A
e	27 keV	0.1 A
Electron beam temperature		0.2 eV
Temperature angular spread		$2\cdot10^{-3}$
Damping time of protons		3 sec
The proton beam equilibrium dimension		1 mm

G.I.Budker, Ya.S.Derbenev, N.S.Dikansky, V.I.Kudelainen, I.N.Meshkov, V.V.Parkhomchuk, D.V.Pestrikov, B.N.Sukhina, A.N.Skrinsky, First experiments on electron cooling, in Proc. of IVth All-Soviet Conference on Part. Accel., v.2, p.302, 1975; IEEE Trans. Nucl. Sci., NS-22 (1975) 2093; Part. Accelerators 7 (1976)197; Rus. Atomic Energy 40 (1976) 49.

Provisional text
not revised by CERN
Translation Service

NUCLEAR PHYSICS INSTITUTE
SIBERIAN BRANCH OF USSR ACADEMY OF SCIENCE

PS/DL/Note 76-25
October 1976
Preprint N.P.I. 76-32

G.I. Budker, A.F. Bulyshev, N.S. Dikansky, V.I. Kononov, V.I. Kudelainen, I.N. Meshkov, V.V. Parkhomchuk, D.V. Pestrikov, A.N. Skrinsky, B.N. Sukhina

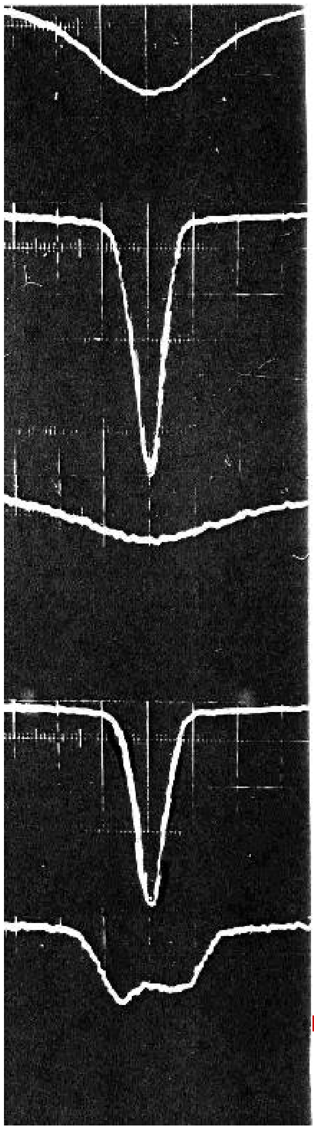
NEW EXPERIMANTAL RESULTS OF ELECTRON COOLING

Presented to the All Union High Energy Accelerator Conference, Moscow, October 1976

(Translated at CERN by O. Barbalat)

* * * * *

Improvements: B-field homogeneity in the cooling section – better than 10^{-4},



electron energy stability – better than 10^{-5}.

As a result - … the betatron oscillation damping time is inversely proportional to the electron current

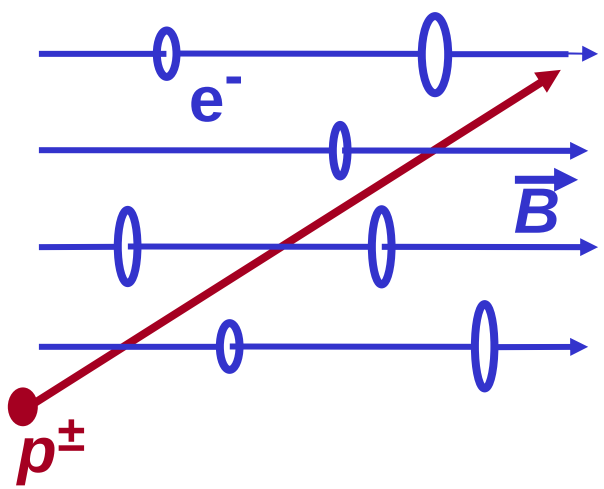
and for a current of 0.8 A it amounts to

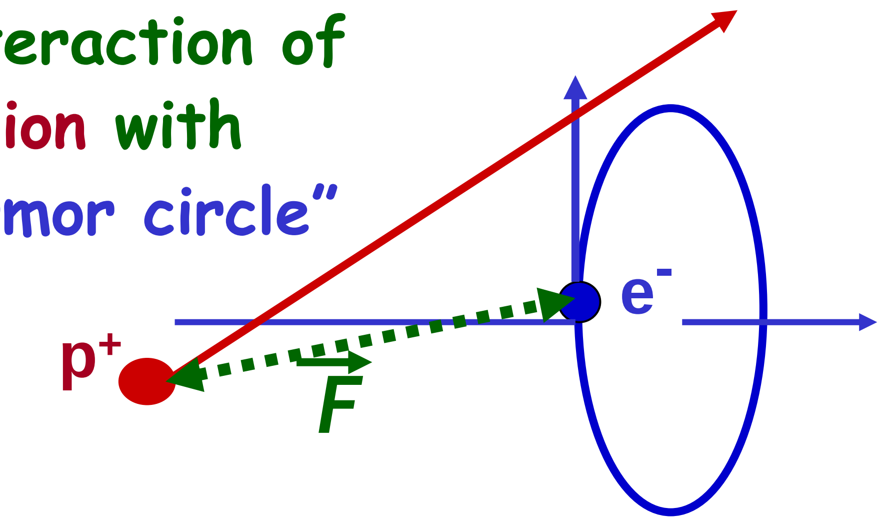
83 ms (proton energy of 65 MeV) –

-much shorter than "The Budker's estimate!"

Improvements

1. Electron beam magnetization (Ya.Derbenev, A.Skrinsky, Rus. Plasma Physics, v.4 (1978) 492)



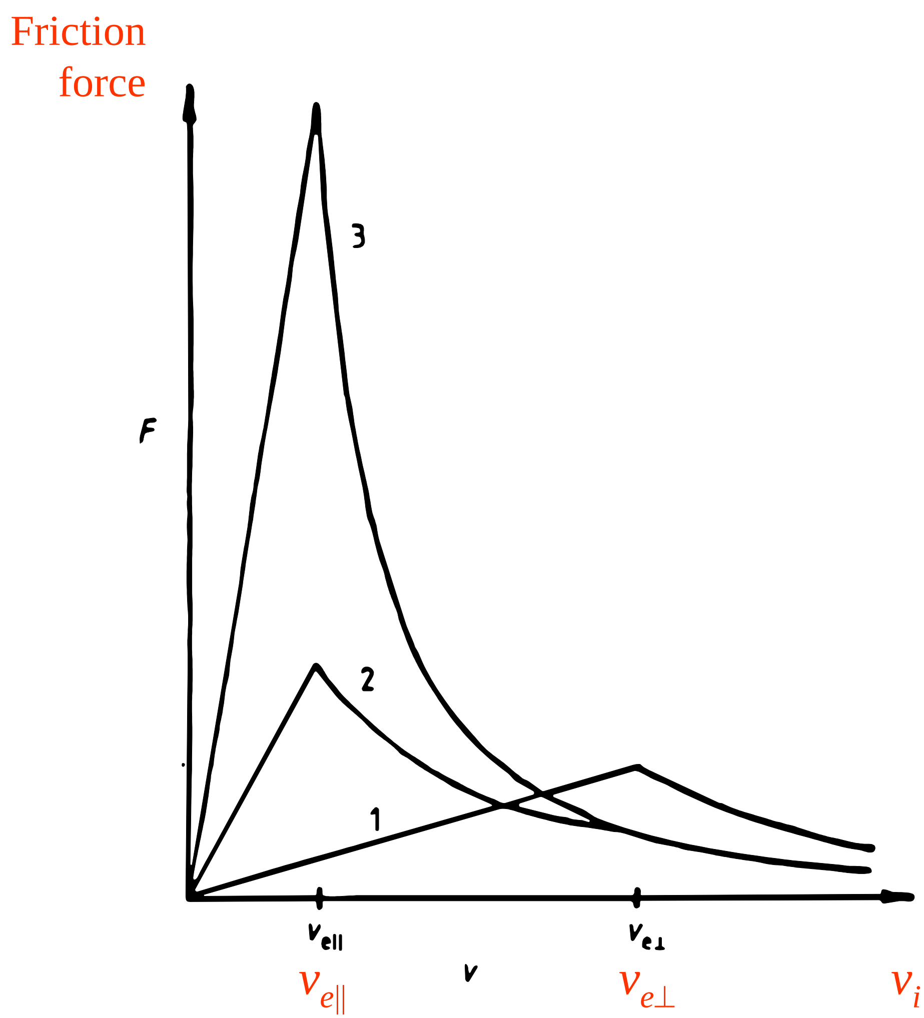


Improvements

2. Flattened velocity distribution of electrons in Particle Rest Frame (longitudinal cooling due to acceleration)

$$T_{\|} = \frac{T^2_{Cathode}}{\beta^2 \gamma^2 mc^2}$$

Transverse friction force for various guiding magnetic field values



From: "Electron cooling: physics and prospective applications", by V.V. Parkhomchuk and A.N. Skrinsky, Rep. Prog. Phys. 54 (1991), p. 919.

Figure 2. Behaviour plotted against friction force at different values of magnetic field. Curve 1: in the absence of magnetic field, curve 2: under the condition of partial magnetization, curve 3: complete magnetization of transverse electron motion.

First cooler rings

Europe – 1977 – 79, Initial Cooling Experiment at CERN

M.Bell, J.Chaney, H.Herr, F.Krienen, S. van der Meer, D.Moehl, G.Petrucci, H.Poth, C.Rubbia– NIM 190 (1981) 237

USA – 1979 – 82, **Electron Cooling Experiment at Fermilab**

T.Ellison, W.Kells, V.Kerner, P.McIntyre, F.Mills, L.Oleksiuk, A.Ruggiero, IEEE Trans. Nucl. Sci., NS-30 (1983) 2370;

Second Generation of Cooler Storage Rings

1988 - IUCF Cooler Ring (Bloomington,IN, USA)

1988 – Test Storage Ring (MPI, Heidelberg, Germany)

1988 – Low Energy Antiproton Ring (CERN)

1989 – TARN-II ("Test Accumulator Ring for NUMATRON, Tokyo University, Japan)

1989 – CELSIUS (Uppsala University, Sweden)

1990 – Experimental Storage Ring (GSI, Darmstadt, Germany)

Second Generation of Cooler Storage Rings

1992 - COoler-SYnchrotron (FZ Juelich, Germany)

1992 - CryRing (MSI, Stockholm, Sweden)

1993 - ASTRID (Aarhus University, Denmark)

1998 - SIS (GSI, Darmstadt, Germany)

2000 - Heavy Ion Medical ACcelerator (NIRS, Japan)

2000 - Antiproton Decelarator (CERN)

2002 - Electrostatic cooler storage ring at KEK (KEK, Tsukuba, Japan)

ESR Electron Cooler at GSI (Darmstadt)

electron beam parameters

energy	1.6–250 keV
current	1 mA – 1 A
diameter	50.8 mm
gun perveance	1.95 μP
collection effic.	> 0.9998
temperature	
transverse	0.1 eV
longitudinal	~ 0.1 meV

magnetic field

strength	0.015 – 0.2 T
straightness	1×10^{-4}

vacuum 2×10^{-11} mbar

Coming soon:

2005 – Recycler Electron Cooler (Fermilab, USA)

200? – Two cooler rings complex (IMP, Lanzhou, China)

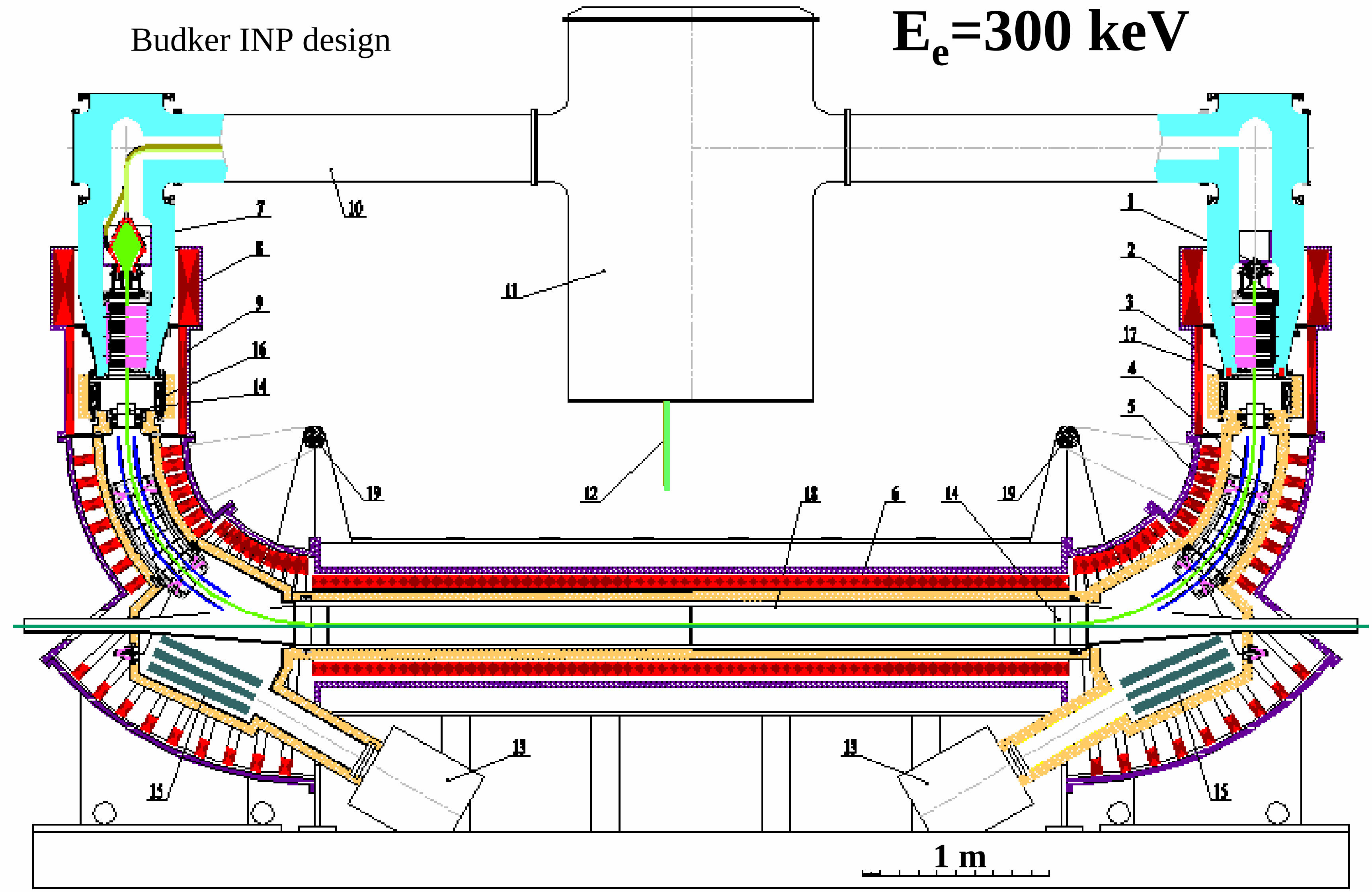
2006(?) - Low Energy Ion Ring (CERN)

20?? –TARN-II–renovated (RIKEN, Japan)

2005 – S-LSR : Solid magnet Laser equipped cooler Storage Ring (Kyoto University, Japan)

Most recent addition to the electron cooling family – a 300-kV cooler at IMP, Lanzhou

- Built and commissioned by Budker INP
- Has implemented several novel ideas:
  - Electrostatic electron beam bends
  - Variable-profile electron beam
  - Extra-uniform (1ppm) guiding magnetic field



1 - electron gun; 2- main “gun solenoid”; 4 - electrostatic deflectors;

5 - toroidal solenoid; 6 - main solenoid; 7 - collector; 8 - collector solenoid; 11 - main HV rectifier; 12 - collector cooling system.

Electron cooling applications

- Particle physics with “electron cooled” protons, deuterons and antiprotons :

  - ✓ **Antiproton physics => *LEAR***
  - ✓ **π-meson physics => *IUCF, COSY, CELSIUS***
  - ✓ **First antihydrogen generation in-flight => => LEAR (stochastic cooling)**
  - ✓ **Antihydrogen generation in traps => => AD => *ATHENA* and *ATRAP***

Electron cooling applications

❖ Nuclear physics

✓**Studies of** radioactive nuclei and rare isotopes, exotic nuclei states (like bare nuclei decay, etc.) =>

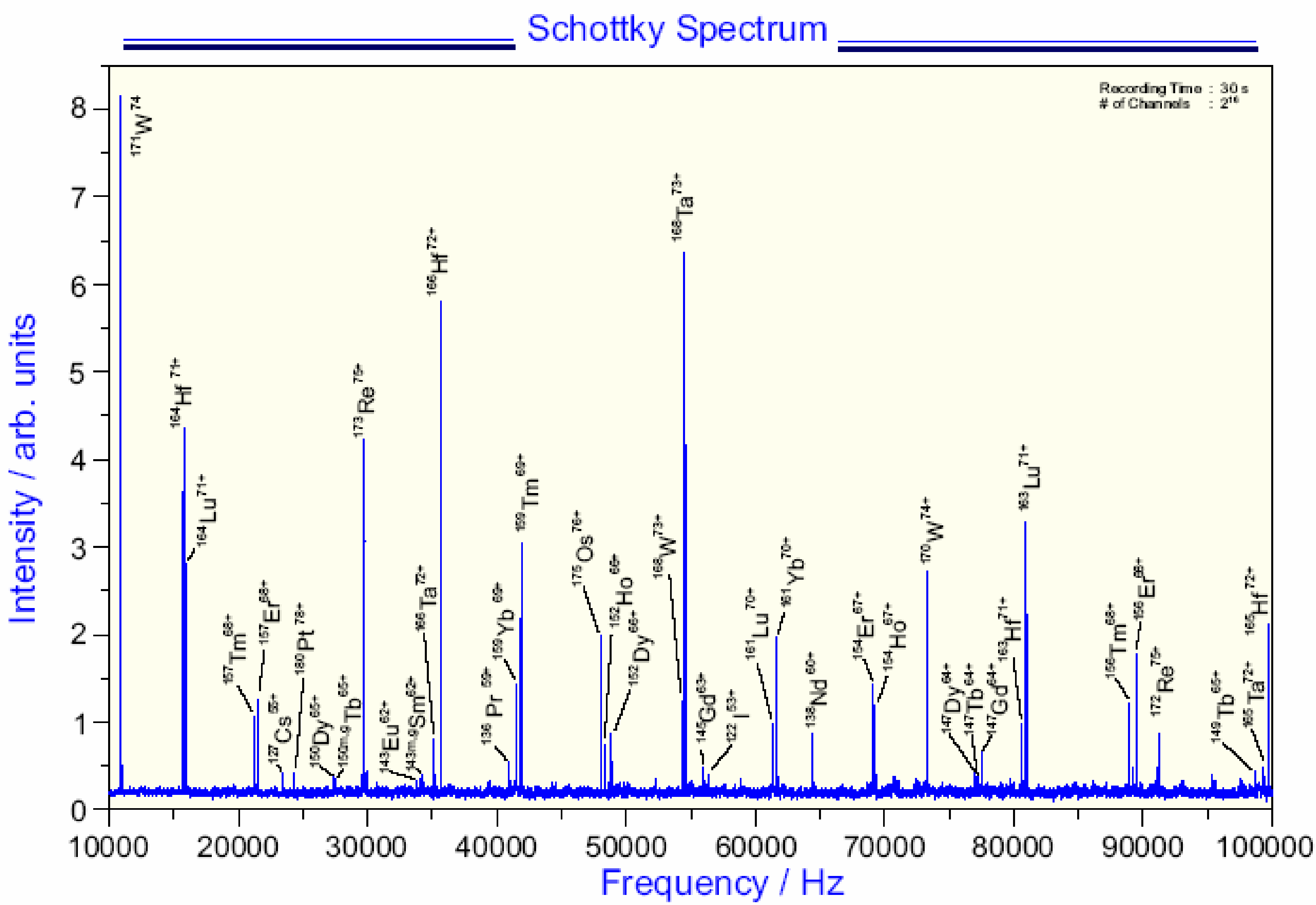
=> *ESR*

✓ **High precision mass spectroscopy => *ESR***

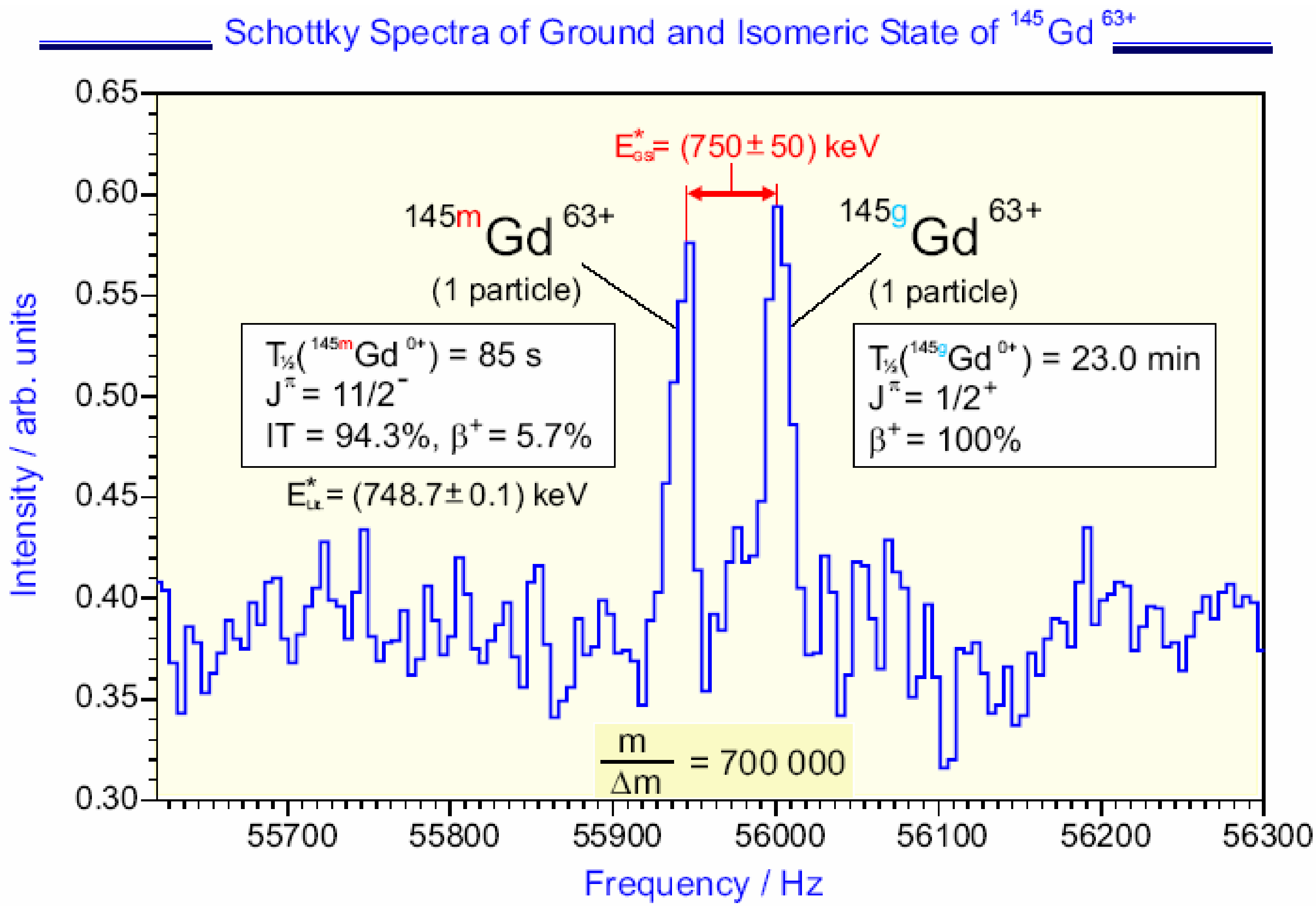
❖ New stage of experiments in atomic and molecular physics =>

=> *TSR, CryRing, ASTRID*

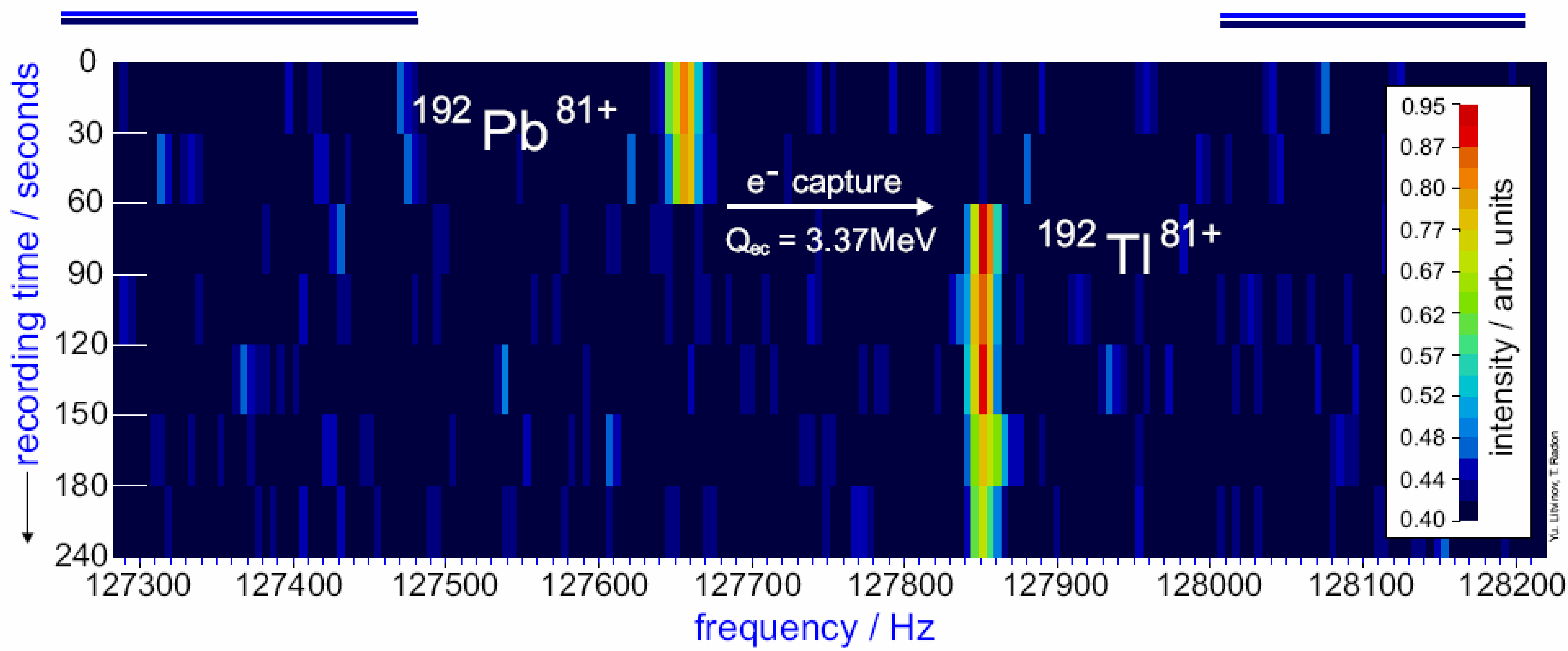
Mass-spectrometry of radioactive nuclei at GSI



Mass spectrometry of excited nuclear states

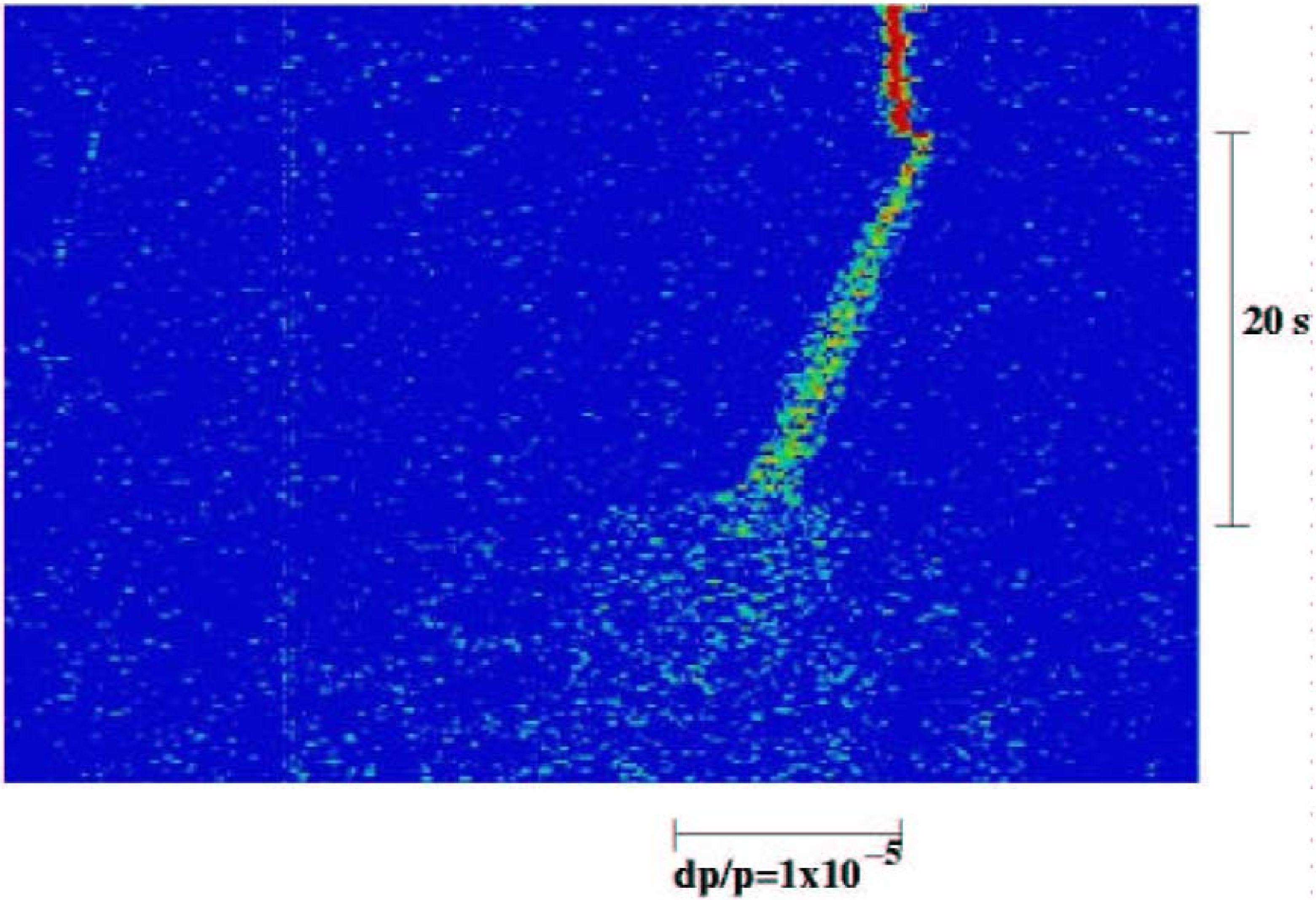


Detection of single cooled ion at GSI

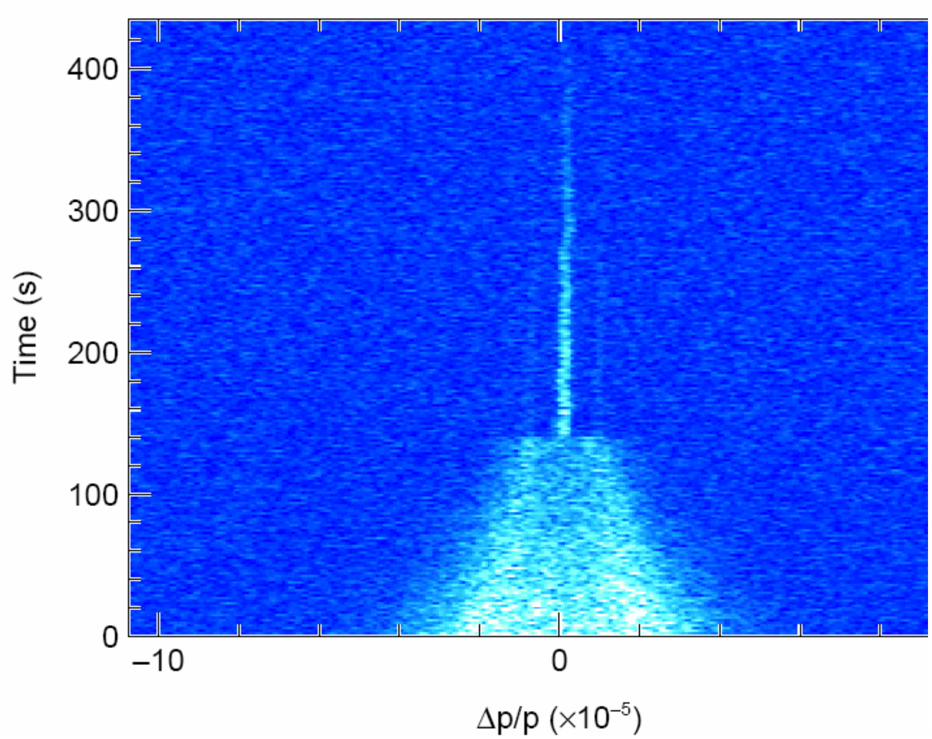


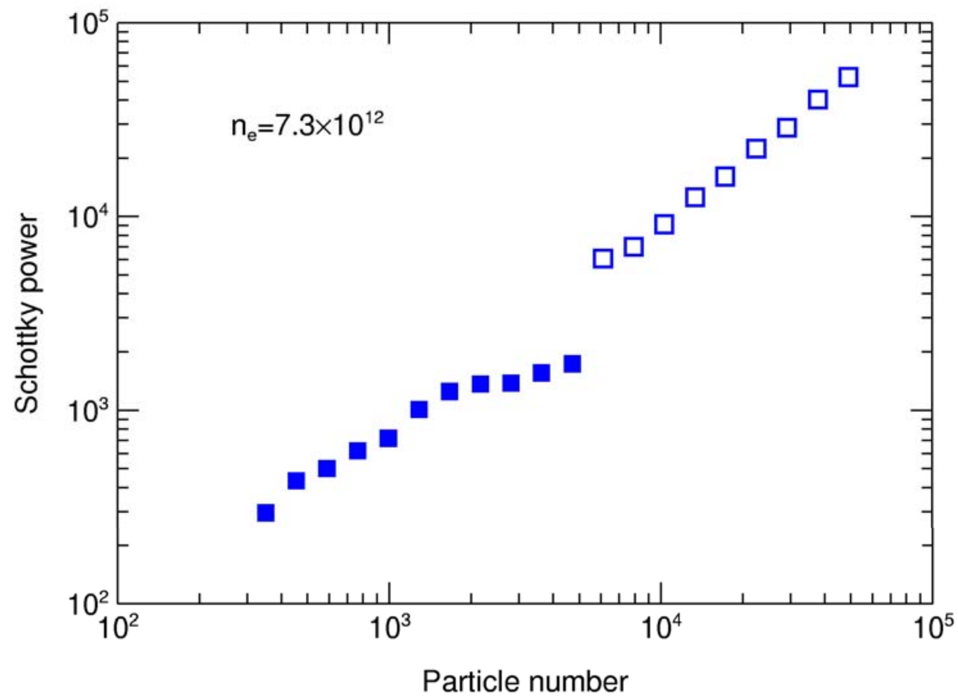
high sensitivity due to well defined revolution frequency and high ion charge (Schottky noise α q^2)

Energy loss by the beam due to residual gas after electron cooling is turned OFF



Ordering effects in coasting and bunched ion beams





CRYRING, Manne Siegbahn Lab
Phase transition to a 1D crystal (string). Min. dist. btw. ions 4 mm

More information in

Phys. Rev. Lett. 88, 174801 (2002)
J. Phys. B 36, 1003 (2003)

Fermilab
Electron Cooling Experiment

Design Report

August, 1978

Participants: J. Bridges, J. Gannon, E.R. Gray, J. Griffin, F.R. Huson, D.E. Johnson, W. Kells, F.E. Mills, C. Moore, G. Nicholls, L. Oleksiuk, T. Rhoades, D.E. Young, Fermilab; P.M. McIntyre, C. Rubbia, Harvard; W.B. Herrmannsfeldt, SLAC; D. Cline, J. Rhoades, Wisconsin.

Fermi National Accelerator Laboratory
Batavia, Illinois

Operated by Universities Research Association Inc.
Under Contract with the United States Department of Energy

APPENDIX I

FERMILAB $\bar{p}$ x p

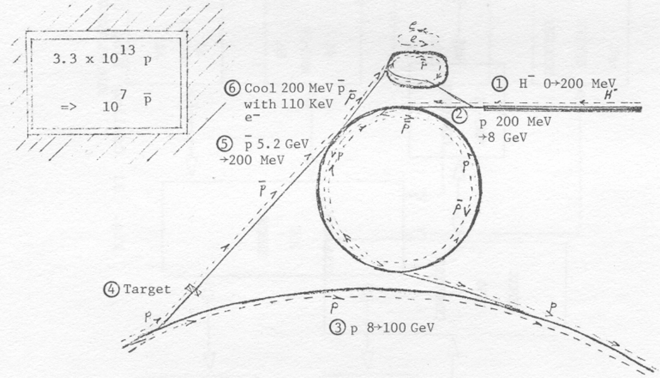
$\sqrt{S}$ = 500/2000 GeV

GOALS: Proton "cooling" experiment

1.	Electron "cool" 200 MeV protons (10^7)	10/78
2.	Accumulate 200 MeV protons (10^{10}) $\bar{p}$ experiment	12/78
3.	First $\bar{p}$ into cooling ring	1/79
4.	First $\bar{p}$ into main ring	3/79

STEP I. PRODUCE $\bar{p}$, DECELERATE $\bar{p}$ COOL $\bar{p}$ (6 SEC.)

1. Accelerate 200 MeV H^- in Linac and inject into booster (normal operation).
2. Strip H^- at injection into booster to load booster with p (normal operation).
3. Inject 8 GeV p into main ring and accelerate to 100 GeV (normal operation).
4. Extract 100 GeV p into target and produce 5.2 GeV $\bar{p}$.
5. Inject 5.2 GeV $\bar{p}$ into booster and decelerate to 200 MeV.
6. Inject 200 MeV $\bar{p}$ into cooling ring and "cool" with 110 KeV e^-.



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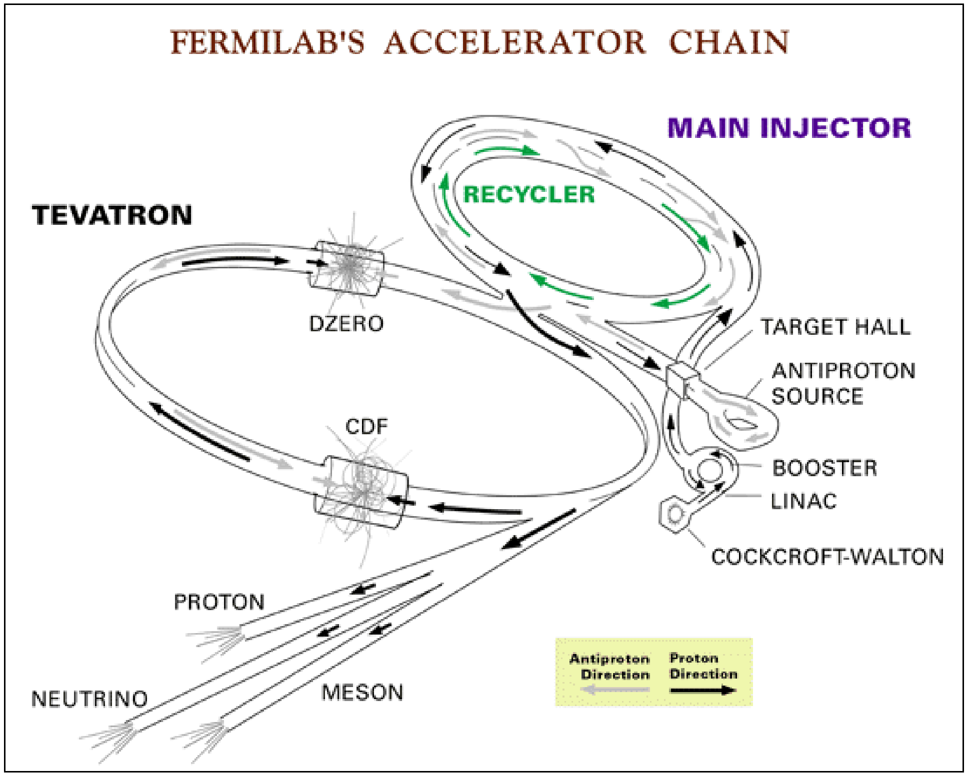
Fred Mills, one of the Fermilab physicists working on the electron cooling tests in 1980, writes:

One of our regular visitors at Fermilab was Kolya Dikansky, who had so brilliantly constructed NAP-M and carried out the INP cooling experiments. When we were close to cooling at Fermilab, Kolya brought us a bottle of vodka. He had written on it simply, "Don't open without cooling."

The first cooling took place at 4:40 AM one morning. Don Young and Peter McIntyre had tuned the ring and electron system all night and I came in at 4:00 AM for the next 12 hour shift. I noticed that although the conditions favored resonance crossing, the beam loss pattern was not usual, so I asked for a few minutes to check the RF. I simply turned down the RF from several kV to 10-15 V, and after a slight frequency adjustment, observed the beam (all 100,000 protons!) cool into a tiny bucket. We immediately called Russ Huson. When Russ arrived, we and others who happened along, opened and drank the vodka according to Kolya's instructions.

Fermilab's legacy: Cool Before Drinking...

Where do we get antiprotons?



The Antiproton Source is made up of three parts. The first is the Target: Fermilab creates antiprotons by striking a nickel target with protons. Second is the Debuncher Ring: This triangular shaped ring captures the antiprotons coming off of the target. The third is the Accumulator: This is the storage ring for the antiprotons. Recently, we have added another ring, the Recycler, for additional antiproton storage.

Recycler – Main Injector

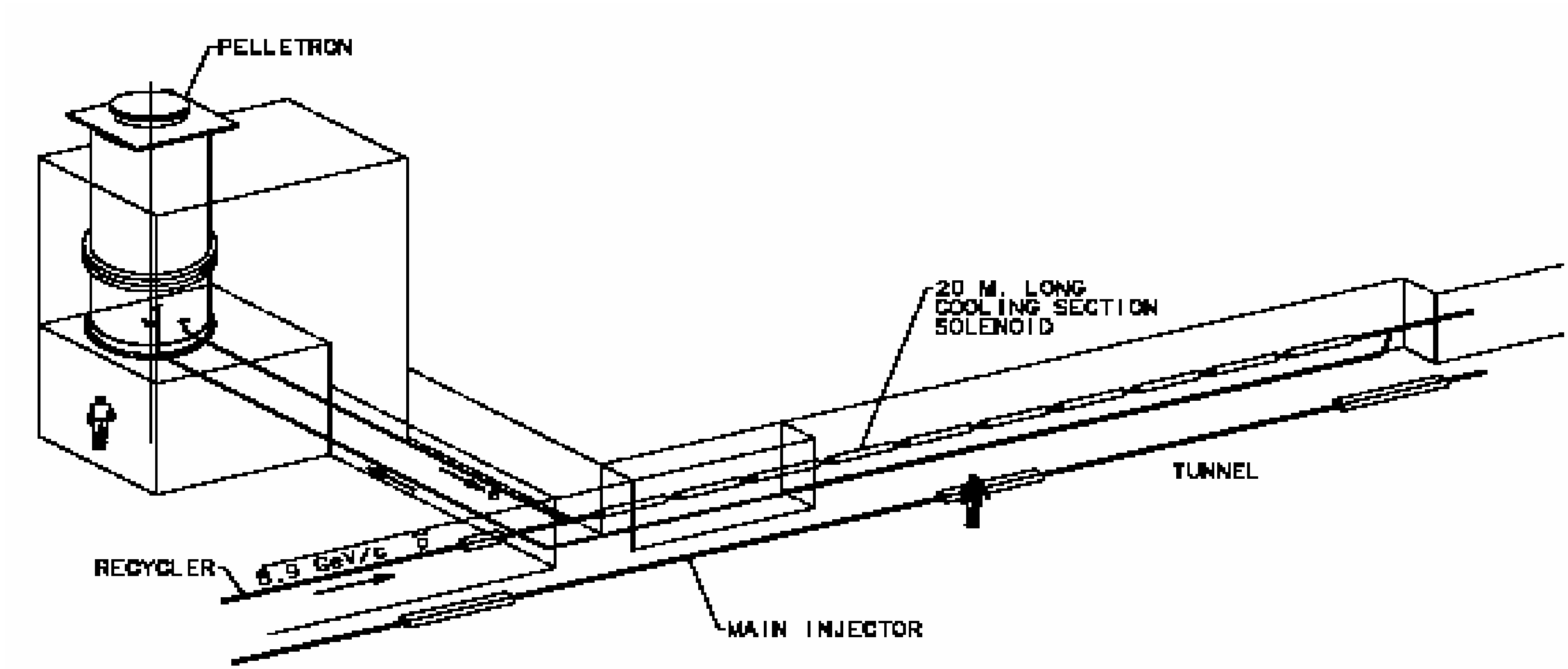
Recycler

Main Injector

The Recycler is a fixed-momentum (8.9 GeV/c), permanent-magnet antiproton storage ring.

The Main Injector is a rapidly-cycling, proton synchrotron. Every 1.5-3 seconds it delivers 120 GeV protons to a pbar production target. It also delivers beam to a number of fixed target experiments.

Schematic Layout of the Fermilab Electron Cooling



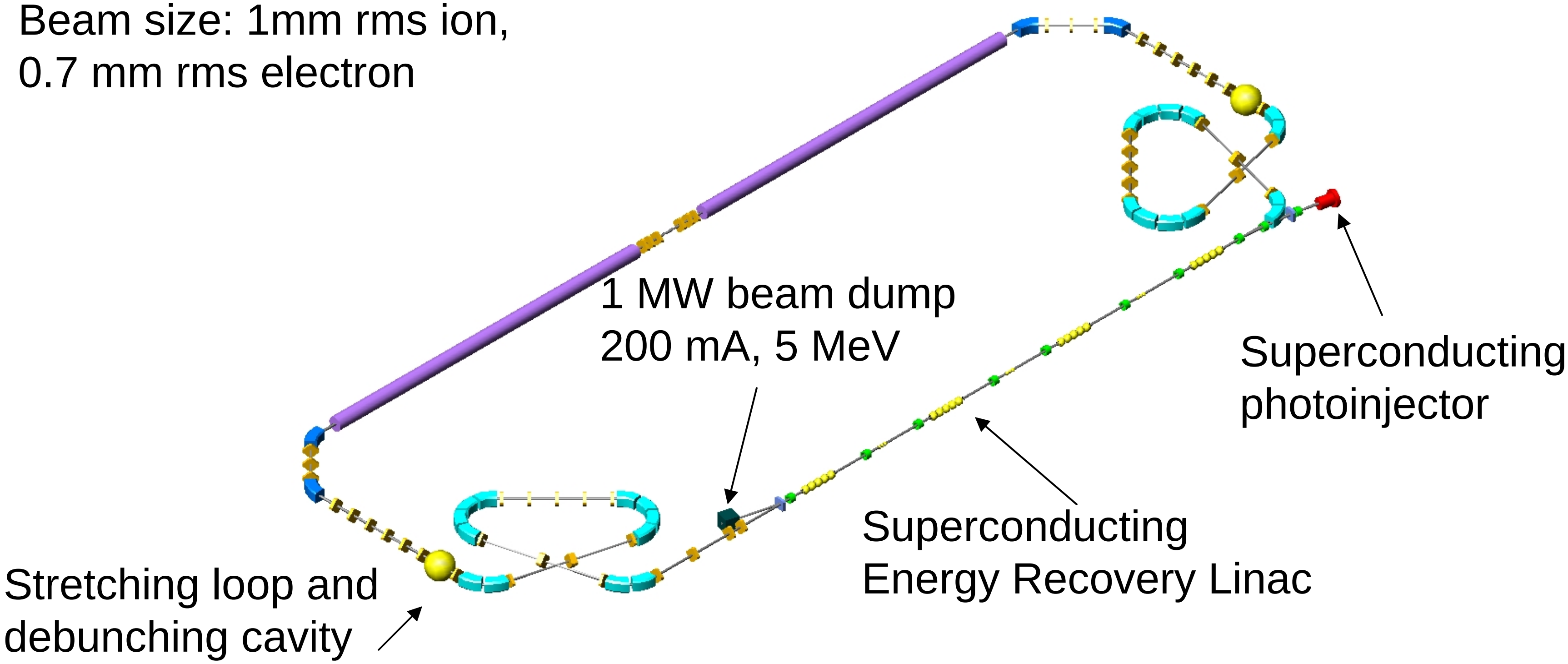
Electron beam parameters

▪ Electron kinetic energy	4.34 MeV
▪ Absolute precision of energy	≤ 0.3 %
▪ Energy ripple	≤ 10^{-4}
▪ Beam current	0.5 A DC
▪ Duty factor (averaged over 8 h)	95 %
▪ Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms	≤ 0.2 mrad

The RHIC Electron Cooler

Two solenoids: 13-m, 50-kG ea.

Beam size: 1mm rms ion,
0.7 mm rms electron



54 MeV electron beam for cooling 100 GeV/A (gold ions and protons.
Must use superconducting Energy Recovery Linac.
Need 20 nC electron bunches at 9.4 MHz.
The emittance is challenging.

Electron Cooling Installation Schedule/Highlights

- 5/04 - MI31 Building Construction Complete
- 5/04 - R&D Operations at Wide Band Complete
- 6/04 - Disassembly/Move of Pelletron Begins
- 8/04 - 13-Week Lab Wide Shutdown Begins (Pelletron Assembly Suspended)
- 11/04 - Lab Wide Shutdown Complete (Pelletron Assembly Resumes)
- 2/05 - Pelletron/E-Cool Installation Complete
- 3/05 - Commissioning Began

Pelletron Disassembly/Move

- Pelletron at Wide Band Lab Before Disassembly (5/04)
  - 1.5 Months to Disassemble

- Lower Half of Pelletron Being Transported to MI31
  - All Components Transported 3-Miles Across the Laboratory

Lab Wide Shutdown

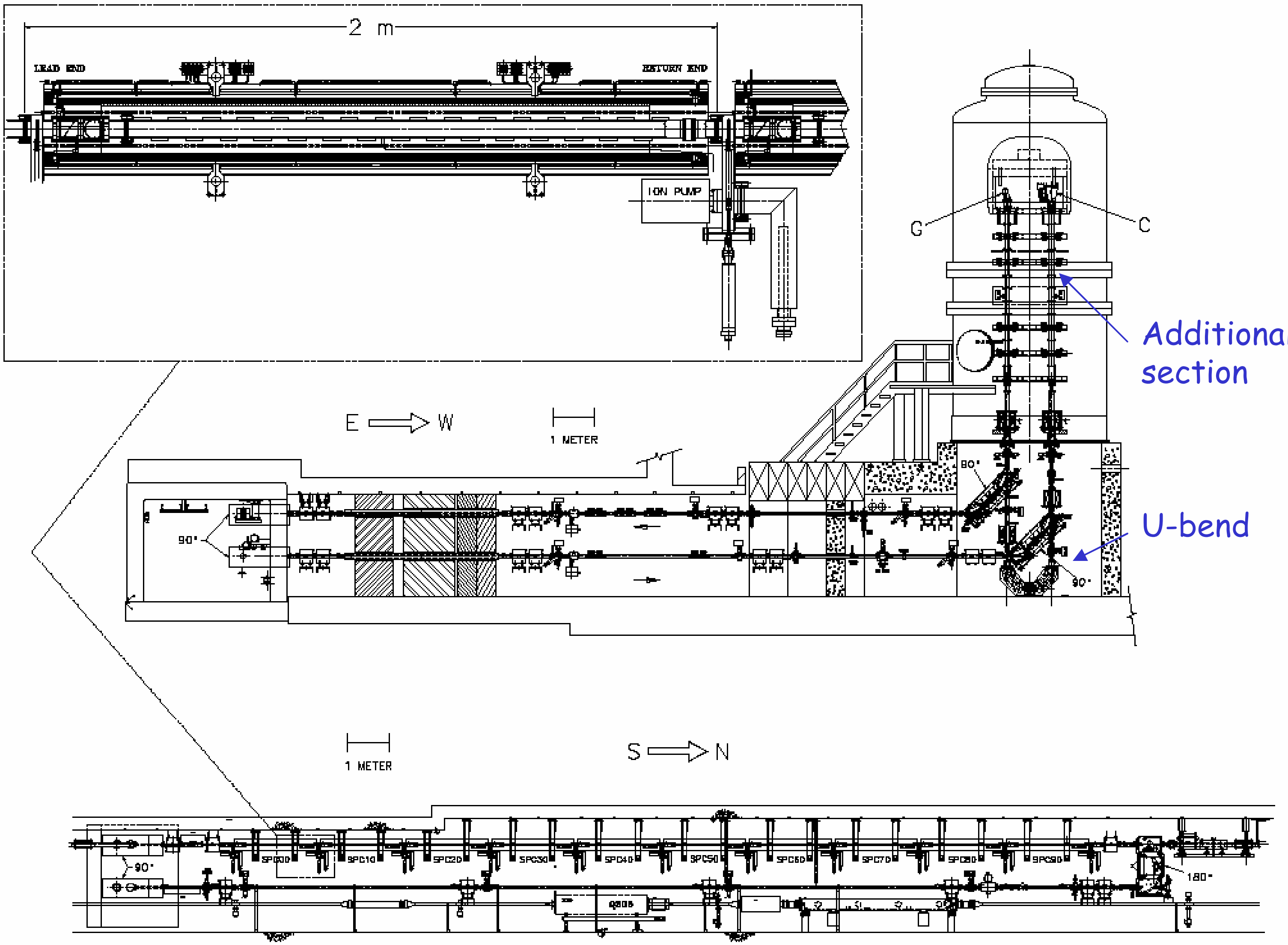
- Before and After Pictures of E-Cool Section of MI Tunnel
  - 13-Week Shutdown
  - Modified MI Utilities, Removed Recycler Section, Installed all Beam Lines
  - Lab-Wide Effort

Cooling section solenoid

Installation at MI31 Building

- Pictures of MI31 Service Building Before and After Installation of Pelletron

Electron cooling setup at MI-30



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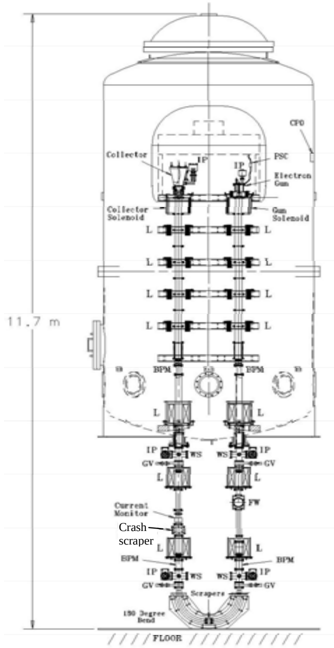
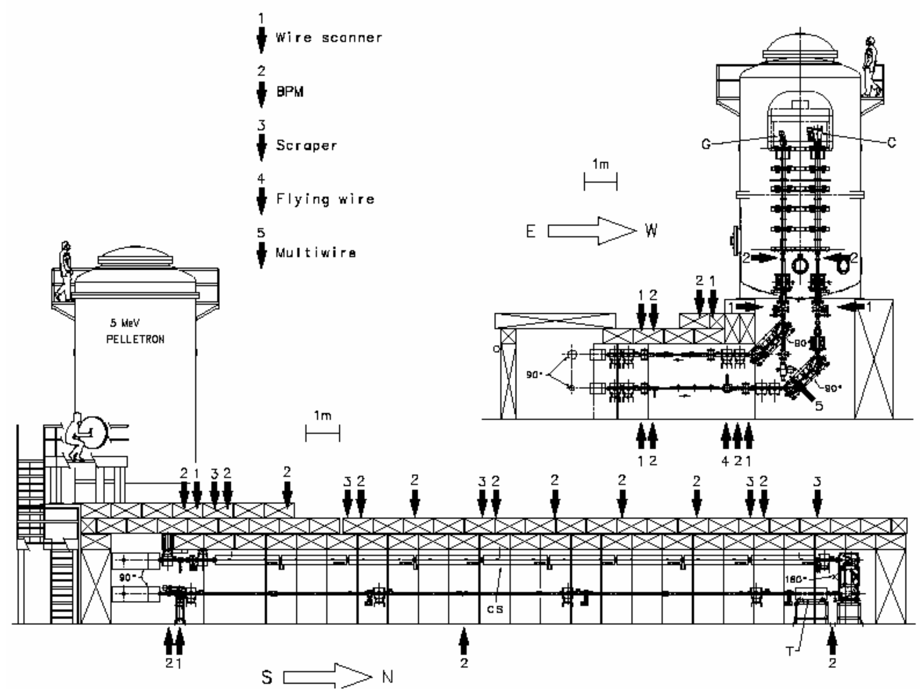
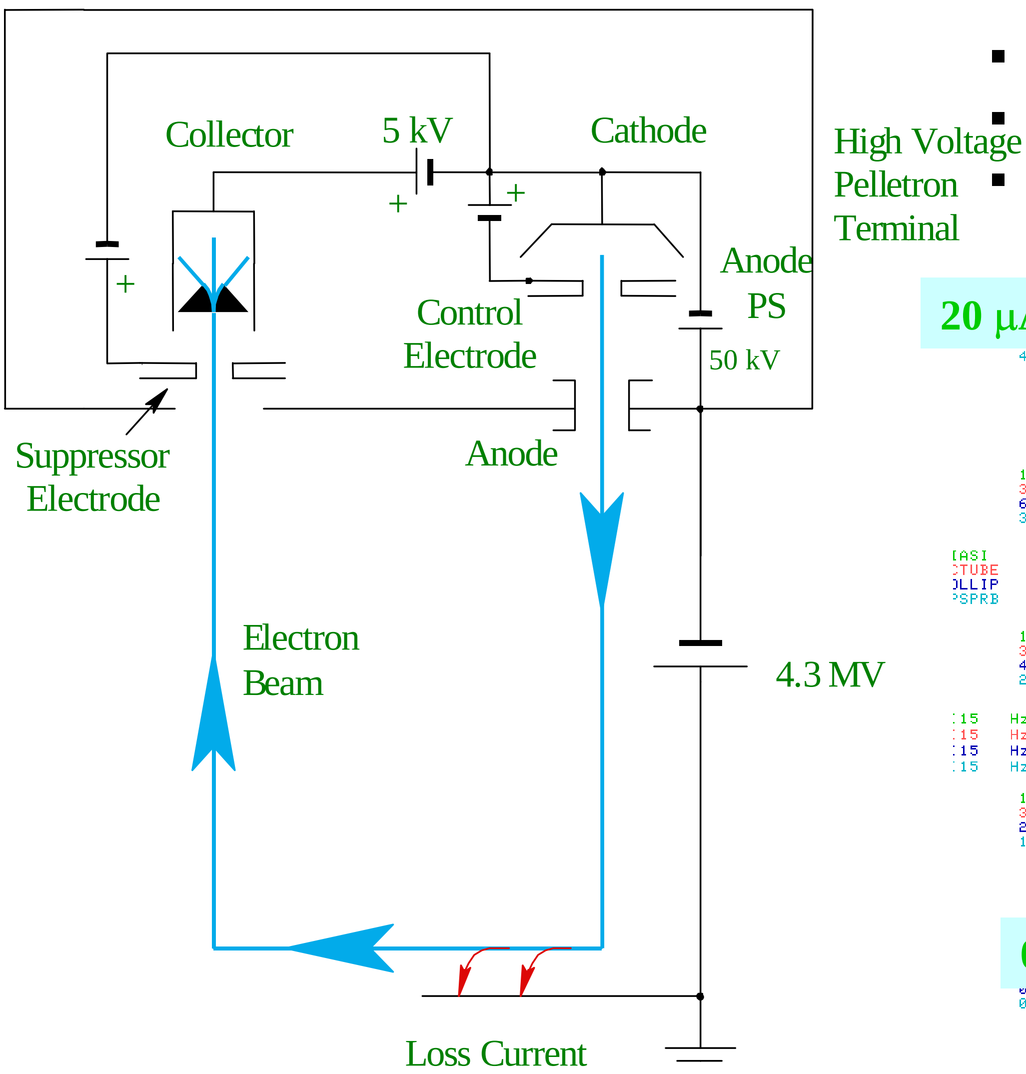
The R&D program at WideBand

- 20-Mar-01- Fist time HV on both tubes
- 28-Dec-01 - 0.6 A in the short beam line
- 18-Nov-02 - Imax=1.7 A; beginning of a shutdown
- 17-Jul- 03 - DC beam recirculated through the full-scale line
- 30-Dec-03- 0.5 A DC beam
- 29-May-04- 0.1 A beam with required beam properties in the cooling section



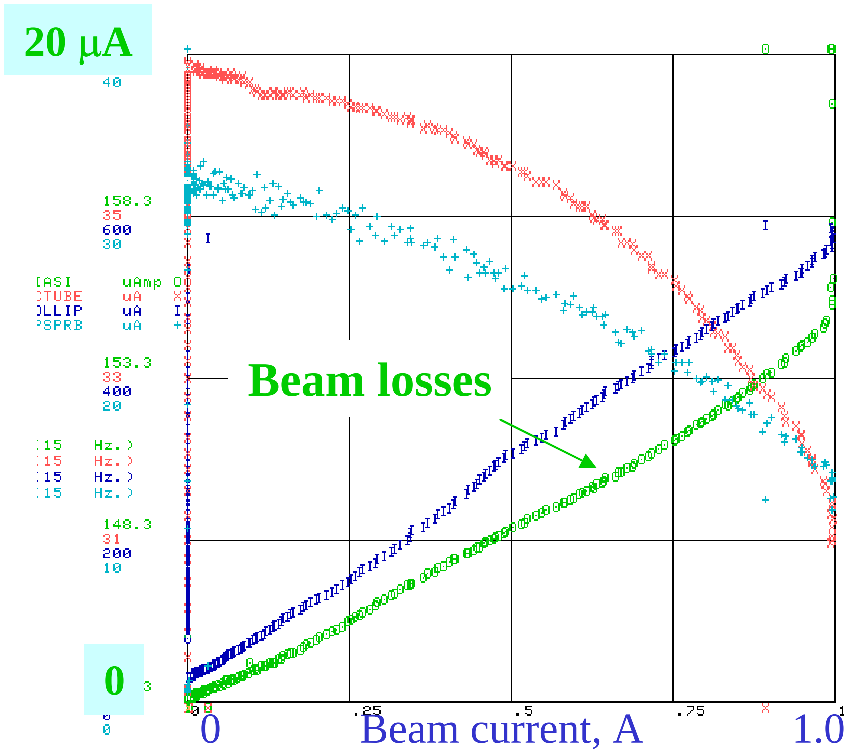


Simplified electrical schematic of the electron beam recirculation system.



For I= 0.5 A, ΔI_{loss}= 5 μA:

- Beam power 2.15 MW
- Current loss power 21.5 W
- Power dissipated in collector 2.5 kW



Summary of electron angles in the cooling section

Component	Upper limit, μrad	WB result, μrad	Measured by	Required resolution of diagnostics
Temperature	90	No meas.	Pepper pot image at OTR monitor	50 μm in the OTR image
Aberration	90	~ 40	Pepper pot image at OTR monitor; BPMs	150 μm in OTR image; 50 μm in BPMs
Envelope scalloping	100	100	Movable orifices	500 μm in beam dimension measurements
Dipole motion caused by magnetic field imperfections	100	~ 200	BPMs	30 μm in “DC” BPM resolution; 50 μm in BPMs’ offsets measured wrt pbar beam
Beam motion	50	30	BPMs	50 μm in BPM signal in 100 Hz bandwidth
Drift velocity	20	No meas.	Calculated	
Total	**200**	**~ 300**		

Milestones

	Plan	Actual
▪ Commissioning begins	02/01/05	03/01/05
▪ U-bend commissioned	03/14/05	04/15/05
▪ Full beamline commissioned	04/04/05	
▪ A 0.5-A DC beam	07/08/05	
▪ Cooling of antiprotons	09/08/05	

Electron cooling commissioning -- summary

- Finished the R&D program on schedule (May 04)
- Prepared and reviewed a commissioning plan (Aug 04)
- Continued detailed modeling of optics, procedures, IBS and cooling rates with the emphasis on commissioning.
- Commissioning high-lights:
  - Pelletron conditioned to 5 MV. Operate at 4.3 MV
  - A dc beam of 0.5-A beam passed thru U-bend to collector with no losses.
  - A 35-mA dc beam passed thru the cooling section.
  - Can co-exist with pbar-beam operations

Electron cooling -- summary

- Electron cooling has become a very useful method in molecular, atomic and nuclear physics. It will soon advance into high-energy physics, just like G. Budker envisioned initially.
- Traditional low-energy electron cooling continues to be the source of new fruitful ideas: hollow electron beams, magnetized cooling with hot electrons, rare-isotope accumulation, ordered beam, halo removal…
- High-energy electron cooling systems are well on their way to overcome technical hurdles.

Acknowledgments

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